# Towards Usable Topological Operators at GIS User Interfaces

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## SUMMARY

*The topological relations defined by formal mathematical models like the nine-intersection are not adequate for user interaction. Human subject tests have shown that people rather use less, grouped, and overlapping relations. But these are only first results and a theory for building cognitively adequate operator sets is missing. This is reflected by the considerably different operator sets of current software products. So far, human subject tests concerning cognitive adequacy of topological operators have followed a general approach detached from human activities. We propose to change the focus and examine which topological relations humans use when accomplishing tasks. The intention is to faster produce realisable results and to come closer to what humans actively deal with.*

**KEYWORDS:** *topological relations, formal models, cognition, usability, standards, GIS*

## INTRODUCTION

Topological relations have been formally defined and extensively studied since more than a decade (Egenhofer & Herring, 1990b; Egenhofer & Herring, 1991; Egenhofer & Sharma, 1993; Egenhofer et al., 1994; Randell et al., 1992; Cui et al., 1993). Software usability in general (Norman, 1986; Helander, 1990; Grudin, 1992; Nielsen, 1993; Raskin, 2000) and specifically in geographical information systems (GIS) (Gould, 1989; Frank, 1993; Kuhn, 1993; Medyckyj-Scott & Hearnshaw, 1993; Davies & Medyckyj-Scott, 1994) has been a research issue just as long. We might consequently assume that GIS user interfaces for topological operators should be easy to use.

In fact, standards today define which topological operators shall be provided (ISO, 2002; ISO, 2000). And current GIS present their users with accepted window interfaces, including graphical representations of the available topological operators. Still, we see difficulties in selecting the appropriate operator for a specific task. This can partly be ascribed to interface design issues like the right amount of information in one graphic, suitable colours, or consistency of names. But the problem lies deeper: before brooding over depiction problems it must be decided which operators to present at the user interface. This paper studies current practice by examining the sets of topological operators proposed in standards and implemented in GIS products, looks at existing theoretical foundations for finding operator sets users need, and finally derives open research issues from the insights gained with the first two steps.

## STANDARDS AND GIS PRODUCTS

The International Organization for Standardization (ISO) so far has standardised for simple features, i.e. features with two-dimensional geometries and linear interpolation between the vertices, which topological operators must be provided. These specifications rest on the idea of pair-wise intersections of interiors, boundaries, and exteriors of two objects resulting in a matrix of four or nine intersections, a method introduced by (Egenhofer & Herring, 1990b). ISO also uses the dimensionally extended method (Clementini et al., 1993), which additionally takes into account the dimension of intersections.

The formal definitions yield jointly exhaustive and pairwise disjoint sets of operators, which is welcome for system implementation. But from a user point of view there is an unpleasant characteristic: these sets are too large for human usage. This conjecture is supported by the fact that for many of the formally distinguished situations there is no single natural language term. While (Egenhofer & Herring, 1990b) named the eight possible relations between two regions, they refrained from doing so e.g. with the 33 relations between two simple lines (Egenhofer & Herring, 1990a). In the Spatial Schema, ISO does not assign names to specific operators either (ISO, 2002). The problem aggravates when extending the original intersection model e.g. with dimension or number of intersections (Franzosa & Egenhofer, 1992; Clementini et al., 1993; Egenhofer, 1993).

From the atomic relations groups of two or more can be formed, which humans in fact do as (Mark & Egenhofer, 1994b) have shown. For relations between two regions, e.g., this leads to 255 different combinations. Assuming that this theoretical variety is not necessary in practice, (Clementini et al., 1993) have developed a set of operators for end user interaction containing five combined relations. ISO adopts this reduced operator set (ISO, 2000).

In addition to the ISO standards we have looked at three GIS products to find out how they treat the diversity of topological operators: ArcGIS[53], GeoMedia[54], and Oracle[55]. ArcGIS and GeoMedia are traditional GIS products. Though Oracle as a database management system belongs to another product type, with its spatial extension it provides a good deal of typical GIS functionality, including topological operators. Furthermore, Oracle's server side functionality is made for incorporating it into GIS clients. This means that the topological operators of two products can appear at one user interface, which is an especially interesting situation.

We have produced a test map with the geometric interpretations (Egenhofer & Herring, 1990a) depict for the topological relations they define, leaving out those involving non-simple lines and adding relations with points. We executed all available topological operations on this map and recorded the results. In addition, we produced several situations with finer topological distinctions than made by the nine-intersection model of (Egenhofer & Herring, 1990a) by varying number and dimension of intersections. We also created topologically identical situations with different metric properties. These situations were used to check if the products discriminate situations on a finer level than the nine-intersection model. It turned out that for our random sample this is not the case.

ISO and all products each define one set of named operators that is overloaded for all combinations of geometry types (which does not mean that there is a non-empty result set for each combination). The number of operators is similar (ISO 8, ArcGIS 9, GeoMedia 9, Oracle 11). Differences exist with respect to the nature of these operators. In contrast to the others Oracle provides more atomic than combined operators. GeoMedia, ISO, and ArcGIS - with in this order increasing frequency - more often present combined operators. ISO and Oracle in addition to the named operators allow for inserting a specific intersection matrix in a general relate operator and permit the user-defined combination of operators in one command. The latter can be realised either by inserting wildcards in a matrix or by combining pre-defined operators with a Boolean "or".

Altogether, the four sources provide 13 different operators for region/region relations, 16 for line/line, 15 for region/line, two for point/point, and four for line/point respectively region/point. Figure 1 shows how much the four sources agree on the definition of these operators. The fact that for all relations with points only a very limited number of operator combinations exists explains why the agreement is considerably high: at least three of four sources agree on a definition. The picture is different for the other geometry type combinations. With region/line relations the majority of operators are provided only by one source and the percentage of operators is decreasing towards four agreeing sources. A similar trend is observable

[53] ArcGIS 8.3 (ESRI)
[54] GeoMedia Professional 5.1 (Intergraph Corp.)
[55] Oracle 9*i* Release 2 Spatial (Oracle Corp.)

with line/line relations. Only for region/region relations we find a high percentage with three agreeing sources. This should also be due to the relative small number of eight atomic operators compared to the 19 respectively 33 atomic operators of the preceding geometry combinations.

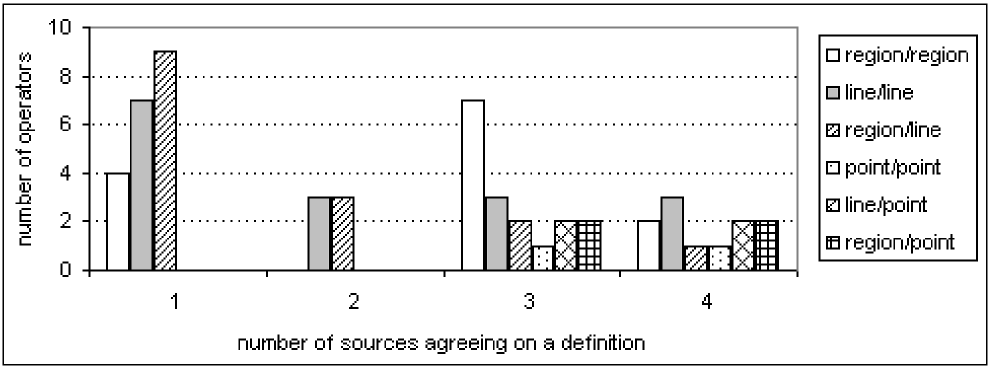


*Figure 1:* Agreement of four sources (ISO, ArcGIS, GeoMedia, Oracle) on topological operator definitions

## FORMAL MODELS AND HUMAN COGNITION

Formal models are good for understanding a domain in its entirety, for identifying the building blocks and discovering the structure. This is needed for implementation, but it is difficult to convey to the user. Obviously it is not desirable to present the mathematical formulas at the user interface. Natural language does not provide enough terms and is ambiguous. Graphics seem to be a good solution, but topological relations cannot be depicted without "overspecifying" them by constraining metrics. Drawing (prototypical) situations might lead the user to thinking that a specific (not prototypical) situation with the same topological relation does not belong to this category. Yet, these are secondary issues.

The primary problem is that formal models do not necessarily correspond to human cognition and human needs (Clementini et al., 1993; Mark & Egenhofer, 1994b). Therefore, it must first be decided what to depict at the interface and then how to do that. (Clementini et al., 1993) propose a reduced operator set they claim to be usable for end-user interaction. As they do not inform about the selection criteria and did not do human subject testing, it must be assumed that they were guided by intuition. The situations in figure 2 are both examples of the relation "line crosses area" as defined by (Clementini et al., 1993). In contrast to this, (Mark & Egenhofer, 1994b) have found in their human subject tests that these are prototypes of two different situations: a) "road enters park" and b) "road crosses park". They found that a road crossing a park cannot have an end inside the park.

a) b)

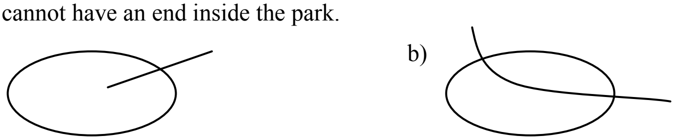

*Figure 2:* Two topological relations between a line and a region

Of course the perception of abstract geometries need not correspond to that of real world features. Still, this example suggests being sceptical regarding intuition. This is supported by (Knauff et al., 1997) who conclude from empirical studies that sets of five operators are not cognitively adequate for relations between regions. Although their sets of five operators are different from that of (Clementini et al., 1993), their finding that a group of eight relations seems a relevant level of conceptualizing spatial configurations is interesting. A subsequent study even proposes to refine the eight relations (Renz et al., 2000). Still, the tendency towards a reduced set of relations at least for the geometry combinations with a larger number of possible relations is confirmed by (Mark & Egenhofer, 1994b; Mark & Egenhofer, 1995) who found five prevailing relations for lines and regions.

The systematic human subject testing with line/region relations ("road/park series") among others has yielded the following results (Mark & Egenhofer, 1994b; Mark & Egenhofer, 1994a; Mark & Egenhofer, 1995). Humans make use of all details distinguished by the nine-intersection model. Humans group the relations defined by the nine-intersection model. There is no set of jointly exhaustive and pairwise disjoint spatial predicates satisfying all queries or natural language descriptions.

(Mark et al., 1995) have proposed an extensive research agenda with a number of test types in order to promote the exploration of cognitively adequate topological relations. So far, grouping, drawing and agreement tasks have been utilised. The grouping and agreement tasks provide subjects with drawings that in the performed tests depicted nine-intersection relations. It can be concluded that these tests reveal what humans in principle can distinguish based on the formally derived relations. This need not correspond to what humans can produce when they do not see these stimuli. They presumably would not end up with all possible relations when asked to draw as many different spatial relations as they can (this would be the graphic examples task which has not been used yet). This might be similar to passive and active vocabulary: humans can passively recognise and distinguish more than they can actively produce. The drawing task (draw a spatial situation according to a given sentence) is more active in this sense. However, the sentences are still given and not produced by the subjects.

All executed tests have in common that they try to examine an understanding of topological relations detached from human activities. (Mark & Egenhofer, 1994b) could be interpreted as having pointed in a more application related direction when they suggested changing the real world phenomena, testing spatial queries provided in GIS software, or taking spatial relations from literature. It will indeed be interesting to see what humans really deal with when accomplishing real life tasks instead of working with mathematically founded sets of situations or arbitrarily compiled term lists.

## CONCLUSIONS AND OUTLOOK

The formalisation of topological relations has been an important achievement for the implementation of queries in GIS. Yet, this is not a final solution from a usability point of view. Human subject tests have proven that the formally derived operator sets need to be reduced and have yielded first hints. But so far a theory how to group topological operators is missing and intuitive solutions in GIS products lead to considerably differing operator sets. Even if all products adhered to the ISO standards this would only enable software interoperability, but no interoperability between software and user, i.e. usability.

Our suggestion for future work is to follow a task centred approach that asks which topological operators humans need when they accomplish tasks. We see two major advantages of this approach. On the one hand, this will faster lead to results relevant in practice that can be implemented in software. On the other hand, this should give more insight in how people perceive objects and their relations which might be quite different from what mathematical models suggest.

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## BIBLIOGRAPHY


Clementini, E. et al. 1993. "A Small Set of Formal Topological Relationships Suitable for End-User Interaction". In: Abel, D. J. and B. Chin Ooi (Eds). Advances in Spatial Databases, 3rd International Symposium, Singapore (SSD '93). Berlin: Springer. Lecture Notes in Computer Science 692. 277-295.

Cui, Z. et al. 1993. "Qualitative and Topological Relationships in Spatial Databases". In: Abel, D. J. and B. Chin Ooi (Eds). Advances in Spatial Databases, 3rd International Symposium, Singapore (SSD '93). Berlin: Springer. Lecture Notes in Computer Science 692. 296-315.

Davies, C. and D. Medyckyj-Scott. 1994. "GIS Usability: Recommendations Based on the User's View". IJGIS 8(2). 175-189.

Egenhofer, M. J. 1993. "A Model for Detailed Binary Topological Relationships". Geomatica 47(3&4). 261-273. http://www.spatial.maine.edu/~max/dimCountTopRel. pdf.

Egenhofer, M. J. et al. 1994. "Topological Relations between Regions with Holes". IJGIS 8(2). 129-142.

Egenhofer, M. J. and J. R. Herring. 1990a. Categorizing Binary Topological Relations between Regions, Lines, and Points in Geographic Databases. Technical Report. 1990. Orono: Department of Surveying Engineering, University of Maine. http://www.spatial.maine.edu/~max/9intReport.pdf.

Egenhofer, M. J. and J. R. Herring. 1990b. "A Mathematical Framework for the Definition of Topological Relationships". In: Brassel, K. E. and H. Kishimoto (Eds). 4th International Symposium on Spatial Data Handling (A Mathematical Framework for the Definition of Topological Relationships). 2/2. Zurich: Department of Geography, University of Zurich. 803-813.

Egenhofer, M. J. and J. R. Herring. 1991. Categorizing Binary Topological Relations between Regions, Lines, and Points in Geographic Databases. Technical Report. 1991. Orono: Department of Surveying Engineering, University of Maine. http://www.spatial.maine.edu/~max/9intReport.pdf.

Egenhofer, M. J. and J. Sharma. 1993. "Topological Relations between Regions in $R^2$ and $Z^2$". In: Abel, D. J. and B. Chin Ooi (Eds). Advances in Spatial Databases, 3rd International Symposium, Singapore (SSD '93). Berlin: Springer. Lecture Notes in Computer Science 692. 316-336.

Frank, A. U. 1993. "The Use of Geographical Information Systems: the User Interface Is the System". In: Medyckyj-Scott, D. and H. M. Hearnshaw (Eds.). Human Factors in Geographical Information Systems. London: Belhaven Press. 15-31.

Franzosa, R. D. and M. J. Egenhofer. 1992. "Topological Spatial Relations Based on Components and Dimensions of Set Intersections". In: International Society for Optical Engineering (SPIE) (Topological Spatial Relations Based on Components and Dimensions of Set Intersections). Boston. Vision Geometry 1832. 236-246.

Gould, M. D. 1989. "Human Factors Research and Its Value to GIS User Interface Design". In: GIS/LIS, Orlando, Florida, USA (GIS/LIS '89). 2/2. 541-550.

Grudin, J. 1992. "Utility and Usability: Research Issues and Development Contexts". Interacting with Computers 4(2). 209-217.

Helander, M. (Ed.). 1990. Handbook of Human-Computer Interaction. 2nd ed.: Elsevier Science.

ISO. 2000. Geographic Information - Simple Feature Access - Part 1: Common Architecture. Draft International Standard (DIS) Projekt-Nr. 19125-1. 29.09.2000: International Organization for Standardization (ISO), Technical Committee (TC) 211.

ISO. 2002. Geographic Information - Spatial Schema. Final Draft International Standard (FDIS). 09.09.2002: International Organization for Standardization (ISO), Technical Committee (TC) 211. http://www.iso.org/iso/en/CatalogueDetailPage.Catalogue Detail?CSNUMBER=26012&ICS1=35&ICS2=240&ICS3=70.

Knauff, M. et al. 1997. "A Cognitive Assessment of Topological Spatial Relations: Results from an Empirical Investigation". In: Hirtle, S. C. and A. U. Frank (Eds). Spatial Information Theory: A Theoretical Basis for GIS, Laurel Highlands, Pennsylvania, USA (COSIT '97). Berlin: Springer. Lecture Notes in Computer Science (LNCS) 1329. 193-206. ftp://ftp.informatik.uni-freiburg.de/documents/papers/ki/knauff-etal-cosit97. ps.gz.

Kuhn, W. 1993. "Metaphors Create Theories for Users". In: Frank, A. U. and I. Campari (Eds). Spatial Information Theory: A Theoretical Basis for GIS, Marciana Marina, Elba Island, Italy (COSIT '93). Berlin: Springer. Lecture Notes in Computer Science (LNCS) 716. 366-376.
Mark, D. M. et al. 1995. "Evaluating and Refining Computational Models of Spatial Relations Through Cross-Linguistic Human-Subjects Testing". In: Frank, A. U. and W. Kuhn (Eds). Spatial Information Theory: A Theoretical Basis for GIS, Semmering, Austria (COSIT '95). Berlin: Springer. Lecture Notes in Computer Science (LNCS) 988. 553-568. http://www.geog.buffalo.edu/~dmark/COSIT95.html.
Mark, D. M. and M. J. Egenhofer. 1994a. "Calibrating the Meanings of Spatial Predicates From Natural Language: Line-Region Relations". In: Waugh, T. C. and R. G. Healey (Eds.). Advances in GIS Research, 6th International Symposium on Spatial Data Handling, Edinburgh, Scotland, UK. Edinburgh: Department of Geography, University of Edinburgh. 538-553. http://www.geog.buffalo.edu/~dmark/SDH94.pdf.
Mark, D. M. and M. J. Egenhofer. 1994b. "Modeling Spatial Relations between Lines and Regions: Combining Formal Mathematical Models and Human Subjects Testing". Cartography and Geographical Information Systems 21(3). 195-212. http://www.geog.buffalo.edu/~dmark/CaGIS.pdf.
Mark, D. M. and M. J. Egenhofer. 1995. "Topology of Prototypical Spatial Relations Between Lines and Regions in English and Spanish". In: Peuquet, D. J. (Ed.) 12th International Conference on Automated Cartography, Charlotte, North Carolina, USA (Auto Carto 12). 245-254. http://www.geog.buffalo.edu/~dmark/AC12.pdf.
Medyckyj-Scott, D. and H. M. Hearnshaw (Eds.). 1993. Human Factors in Geographical Information Systems. London: Belhaven Press.
Nielsen, J. 1993. Usability Engineering. Boston: AP Professional.
Norman, D. A. 1986. "Cognitive Engineering". In: Norman, D. A. and S. W. Draper (Eds.). User Centered System Design. Hillsdale, New Jersey: Lawrence Erlbaum Associates. 31-61.
Randell, D. A. et al. 1992. "A Spatial Logic Based on Regions and Connection". In: Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference, Los Altos (A Spatial Logic Based on Regions and Connection). Morgan Kaufmann. 165-176. http://www.comp.leeds.ac.uk/ qsr/pub/KR92.ps.
Raskin, J. 2000. The Humane Interface. New Directions for Designing Interactive Systems. Addison Wesley.
Renz, J. et al. 2000. "Towards Cognitive Adequacy of Topological Spatial Relations". In: Freksa, C. et al. (Eds.). Spatial Cognition II - Integrating Abstract Theories, Empirical Studies, Formal Models, and Practical Applications. Berlin: Springer. Lecture Notes in Computer Science (LNCS) 1849. 184-197. http://www.dbai.tuwien.ac.at/staff/ renz/papers/spatcog2-rrk.ps.gz.